REMARKS

The Applicants again thank the Examiner for his thorough review of the present application in which claims 7-14 are currently pending. The Applicants also thank the Examiner for conducting a telephone interview regarding potential claim amendments. In the outstanding office action, the Examiner has again rejected claims 7-12 under §103(a) in view of several Japanese references. In response, the Applicants have amended claim 7 and, as discussed below, believe that they have overcome the Examiner's rejections. As such, the Applicants respectfully request reconsideration.

Claim Amendments

The Applicants have amended claim 7 to clarify that the tapered portion of each pole tooth extends beyond the windings of the salient portion. This feature is clearly shown in the specification of the pending application and no new matter has been entered.

New Claims

The Applicants have added new independent claims 13 and 14. Claim 13 clarifies that each pole face has an area which is less than an area of a cross section of the pole tooth taken at its non-tapered portion but no less than one-half of the cross-sectioned area. Claim 14 clarifies that each pole tooth has an overall length and that the tapered portion has a length that is approximately one-third of the overall length. Support for these features can be found at page 8 of the application and no new matter has been entered.

Claim Rejections - 35 U.S.C. §103(a)

The Examiner has rejected claims 7-12 under 35 U.S.C. §103(a) as being unpatentable over JP 7-108,355 (the "'355 patent) and further in view of JP 2000-52,006 (the '006 patent) and JP 3-161,153 (the "'153 patent"). The Applicants believe they have traversed the Examiner's §103 rejection through the arguments presented below.

To establish a *prima facie* case of obviousness of a claimed invention, each and every claim limitation must be taught or suggested by the prior art. *See* MPEP 2143.03. Significantly, the '006 patent fails to teach or suggest an "inwardly *salient* pole tooth" as recited in claim 7." Moreover, the '006 patent fails to teach or disclose a salient pole tooth having at the end of its salient part a lateral taper that extends *beyond the electrical winding*. The remaining references, the '355 and '153 patents, add nothing to the teachings of the '006 patent with respect to the missing elements.

As an initial matter, the Applicants would like to clarify their understanding of "salient" pole tooth. A salient pole is one in which electrical windings do not extend to the tip of the pole, e.g., the pole is conspicuous and protrudes from beyond the winding. In contrast, it is Applicants' understanding that a non-salient pole is one in which the windings extend along the entire length of a pole rendering the pole inconspicuous. This distinction is significant in that it affects the functionality of the poles and the electromagnetic inductor in general. Applicants' understanding of the terms salient and non-salient is well known in the art.

For example, U.S. Pat. No. 3,731,533 issued on May 8, 1973 defines the terms and graphically depicts salient and non-salient poles. FIG. 16 depicts a prior art salient pole 14 which clearly protrudes from the coil 16. In contrast, FIG. 8 depicts non-salient poles which are entirely covered by the coils 94, i.e., no part protrudes from the coil. The patent further states that salient poles are "visually prominent" and "conspicuous", i.e., protruding from the coils, and non-salient poles are "not visible", i.e., entire length is covered by the coil. *See* '533 patent, col. 7, lines 5-25. A copy of the patent is attached for the Examiners review.

Additionally, Applicant has attached a paper summarizing salient and non-salient (cylindrical) poles. The paper specifically states that salient poles are those that "protrude" from the rotor.

In view of the above, the '006 patent does not disclose teach or suggest a *salient* pole tooth with a taper on the portion of the tooth *outside the winding*. Moreover, the '006 patent specifically discloses creating a non-salient pole by extending the winding

along the entire length of each pole. Indeed, the translation of the '006 patent states that it is desirable to "roll an exiting coil 6 so that the *whole* magnetic pole may be covered." *See* '006 patent translation page 7 of 10 (emphasis added). The patent further posits that by covering the whole magnetic pole, leakage flux 13 is reduced. *See id.* As stated previously, the '006 patent teaches away from applicant's claimed invention, as it discloses covering an *entire* pole with windings thus creating a non-salient pole tooth to reduce leakage of magnetic flux. Applicants reduce flux not be creating non-salient poles but by tapering the producing pole portion of a *salient* pole.

More specifically, the '006 patent discloses magnetic poles 7 that have a tapered end and a narrow width. *See* '006 patent, FIG. 3. The poles 7 in the '006 patent are tapered simply to accommodate electrical coils 6 which are wound around each pole and extend to the very tip of the poles thus rendering them non-salient. As previously stated, leakage flux is not an issue with non-salient poles because the space between the poles, where flux might otherwise occur, is occupied by electrical conductors. Therefore, the taper does not serve to reduce leakage flux, it is simply necessary to accommodate the extended coils 6 due to the proximity and placement of each pole 7 relative to one another. *See* '006 patent, FIG. 3.

Applicants reiterate that a prior art embodiment is shown in FIG. 6 of the '006 patent wherein a truly salient pole 7 is shown without taper. The leakage flux 13 from this salient pole 7 is quite considerable. Therefore, the '006 patent leads one skilled in the art overcome leakage issues with prior art salient poles (FIG. 6) by extend the winding to the very tip of a pole, thereby eliminating the protruding portion and converting the salient pole to a non-salient pole. This teaches away from Applicant's claimed invention in which flux is reduced *without* a conversion from salient to non-salient.

Claim 7 recites an "electrical winding wound around an inwardly *salient* pole tooth that terminates in a pole face placed facing said nozzle." Moreover, the claim specifies that each pole tooth has "at the end of its salient part, *extending beyond said electrical winding*, a lateral taper that increases the distance by which said pole faces are separated from one another." In view of the above, the tapered portion of each pole

tooth is that which extends *beyond* the electrical winding, hence the "salient" designation. This configuration is in no way described or even hinted at in the '006 patent. The '355 and '153 patents add nothing to the teachings of the '066 patent with respect to the missing limitation.

With respect to FIG. 2 of the '006 patent, the Applicants do not believe that the figure depicts a protruding salient pole. Applicants note that the text of the patent clearly states that the "whole" pole is covered by the coil. FIG. 4, which depicts another embodiment, shows this more clearly. The patent also describes FIG. 4 as showing a coil covering a "whole" pole. Moreover, Applicants note that according to section 2125 of the MPEP, proportions of drawings are not evidence of actual proportions when drawings are not to scale. This is particularly relevant and significant where the text of the reference infers that the drawing is inaccurate as in the present case, i.e., the "whole" pole of FIG. 2 is covered.

Claims 8-12, which depend from claim 7 and contain its limitations, are allowable for the above-cited reasons.

Finally, the specific configurations of pole teeth claimed in newly added claims 13 and 14 are not shown, taught or disclosed in any of the cited references.

CONCLUSION

Applicants believe it has traversed each objection and rejection raised by the Examiner, it is hereby respectfully requested that Examiner withdraw the rejections of claims 7-14 and pass these claims to issue.

If necessary, the Commissioner is hereby authorized in this reply to charge payment or credit any overpayment to Deposit Account No. 13-0235 for any additional fees required under 37 C.F.R. §§ 1.16 or 1.17, particularly, extension of time fees.

Do not hesitate to call Applicants' attorneys at the number below if they may help expedite the prosecution of this application in any way.

Respectfully submitted,

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SYNCHRONOUS MACHINES

The geometry of a synchronous machine is quite similar to that of the induction machine. The stator core and windings of a three-phase synchronous machine are practically identical to that of a three-phase induction machine. The function of the synchronous machine stator is to provide a rotating mmf to the rotor, just as the stator of the induction machine. The synchronous machine rotor, on the other hand, is different than that of the induction machine.

The rotor of the synchronous machine is a rotating electromagnet with the same number of poles as the stator. The poles of the synchronous machine rotor are created by the rotor windings which carry DC currents. Thus, the synchronous machine requires simultaneous AC and DC excitation of the stator (*armature*) windings and the rotor (*field*) windings, respectively. The magnetic moments associated with the poles of the rotor follow the magnetic moments of the stator-generated mmf which rotates at the synchronous speed. In other words, the magnetic fields of the stator and the rotor tend to align themselves. Therefore, under steady state conditions given a constant frequency AC source, the machine speed (n) of a synchronous machine is equal to the synchronous speed (n_s) defined by

$$n = n_s = 120 \, \frac{f}{p} \quad (\text{rpm})$$

where f is the frequency of the AC signal at the stator, and p is the number of poles in the synchronous machine. Thus, the fundamental difference between a synchronous machine and an induction machine is that the rotor currents of the induction machine are induced while those of the synchronous machine are not.

There are fundamentally two types of rotors used in synchronous machines: *salient pole* rotors and *cylindrical* (or *non-salient* pole) rotors (see Figure 6.1, p. 293). These rotors are each well-suited for different applications based on their physical characteristics.

<u>Synchronous Machine Rotor Types</u>

1. *Salient pole rotor* - the individual rotor poles protrude from the center of the rotor, characterized by concentrated windings, non-uniform air gap, larger rotor diameters, used in applications requiring low machine speed and a large number of machine poles (example - hydroelectric generation).

2. *Cylindrical rotor* - the individual rotor poles are produced using a slotted cylindrical rotor, characterized by distributed windings, nearly-uniform air gap, smaller rotor diameters, used in applications requiring high machine speed and a small number of machine poles, typically 2 or 4 poles (example - steam or gas turbine generators).

The cylindrical rotor is typically a solid piece of steel (made from a single forging) for reasons of strength given the high rotational speeds to which the rotor is subjected. The salient pole rotor does not provide the mechanical strength necessary for these high-speed applications. Also, the salient pole rotor presents too much wind resistance when rotating at high speeds.

The DC current required for the rotor is typically provided by an external DC source (commonly referred to as an *exciter*) that is connected to the rotor windings by means of conducting rings (slip rings) that are mounted concentrically on the machine shaft (the slip rings are electrically insulated from the shaft). The stationary contact required to connect the DC source with these slip rings is achieved by means of carbon brushes that make physical contact with the slip rings as they rotate. The carbon brushes make good electrical contact with low friction.

The DC rotor current can also be provided by a rectifying source (converts AC to DC) mounted directly to the machine shaft. This type of configuration is known as *brushless excitation.*

SYNCHRONOUS GENERATOR
(SYNCHRONOUS MACHINE EQUIVALENT CIRCUIT)

The synchronous machine can be operated as a motor or a generator, but the most common application of the synchronous machine is in the power industry as a three-phase generator. The synchronous generator is also sometimes referred to as an *alternator*.

In a synchronous generator, the magnetic field produced by the DC current in the rotor is static in nature (magnetostatic field). However, if the rotor is set in motion by some external force (wind, water, turbine, etc.), the rotating magnetic field produced by the synchronous generator rotor looks like the rotational mmf produced by the AC current in the stator of the induction motor. This rotating mmf changes the magnetic flux with time through the stator windings inducing an emf in the stator terminals according to Faraday's law. The frequency f of the voltage produced at the stator windings is directly related to the mechanical speed of the rotor rotation (n_m) in rpm by

$$f = \frac{n_m p}{120} \quad \text{(Hz)}$$

where p is the number of poles. As previously shown for the induction motor, the induced emf in the stator terminals can be related to the total magnetic flux ψ_m in the magnetic circuit formed by the rotor/air gap/stator according to

$$V_1 = 4.44 N_1 f \psi_m K_{W1}$$

where N_1 is the number of turns in the stator winding and K_{W1} is the stator winding factor. The total magnetic flux through the stator winding is a superposition of the fluxes due to the stator and rotor currents.

$$\psi_m = \psi_{ma} + \psi_{mf}$$

ψ_{ma} - magnetic flux due to stator (armature) current

ψ_{mf} - magnetic flux due to rotor (field) current

Inserting the total stator flux equation into the stator emf equation yields two voltage components which may be defined as

$$V_1 = V_a + V_f$$

where

V_a - phasor stator voltage component due to ψ_{ma}

V_f - phasor stator voltage component due to ψ_{mf}

When the synchronous machine is operated as a generator, the voltage component V_f represents the generated voltage while the voltage V_a represents the response of the stator to the generation process. Solving for the generator voltage gives

$$V_f = V_1 - V_a$$

In the equation above, the $-V_a$ term represents the voltage drop in the generated voltage due to leakage magnetic flux, magnetization of the synchronous machine core, and losses in the stator windings. This relationship can be represented by a simple equivalent circuit as shown below.
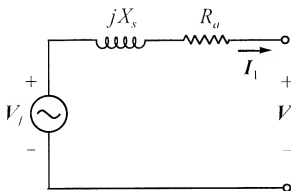
Synchronous machine equivalent circuit

$$V_f = V_1 + I_1 Z_s$$

The impedance $Z_s = R_a + jX_s$ is defined as the *synchronous impedance* where R_a is the *armature effective resistance* and X_s is defined as the *synchronous reactance*. The synchronous reactance contains two components: the leakage reactance X_l and the magnetization reactance X_m.

It is unusual for a synchronous generator to be used to supply a single load. In power systems applications, large numbers of individual synchronous generators are connected to the *power grid* which is sometimes called an *infinite bus*. Large synchronous generators are connected to the power transmission grid located at various locations. These generators are attached to the grid via transformers since the generator output voltage must be stepped up to a higher level for efficient transmission. Various load centers are also connected to the grid throughout the system. These load centers are also attached to the grid via transformers since the load voltage must be stepped down from the transmission voltage level.

Given the large number of generators connected to the power grid, the voltage level and frequency on the power grid stays very stable, even when generators and loads are brought online and taken offline. This is the primary advantage of the infinite bus.

DETERMINATION OF THE SYNCHRONOUS MACHINE EQUIVALENT CIRCUIT PARAMETERS (OPEN-CIRCUIT AND SHORT-CIRCUIT TESTS)

The components of the synchronous reactance can be determined by performing two tests on the synchronous machine: the open-circuit test and the short-circuit test.

Open-Circuit Test   With the stator windings open-circuited, the synchronous machine is driven at synchronous speed while the field current I_f is varied. The open-circuit voltage V_1 across the stator windings is measured. This test provides data for a plot of V_1 vs. I_f. This plot is known as the *open-circuit characteristic* (OCC) and represents the variation of the generator voltage with respect to the field current.

Short-Circuit Test   With the stator input terminals short-circuited (the stator windings connected in parallel), the synchronous machine is driven at synchronous speed while the field current I_f is varied. The current I_1 in each of the three stator windings is measured and an average value is determined. This test provides data for a plot of I_1 vs. I_f. This plot is known as the *short-circuit characteristic* (SCC) and represents the variation of the armature (stator) current with respect to the field current.

The OCC will be nonlinear due to the saturation of the magnetic core at higher levels of field current. The SCC will be linear since the magnetic core does not saturate under short-circuit conditions.
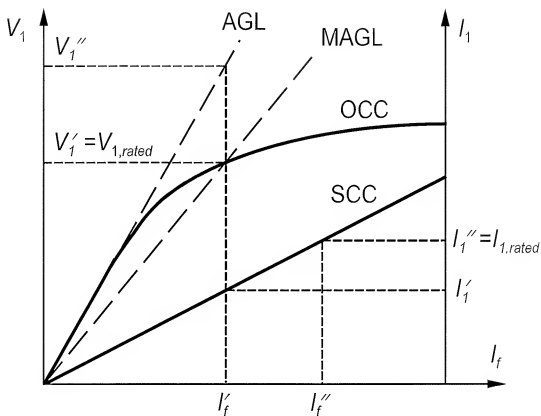
The armature effective resistance R_a is often very small and may be neglected in most problems. If this value is included in the analysis, it will typically be provided.

Determination of the Synchronous Reactance

According to the connections made in the open-circuit and short-circuit tests, the value of the synchronous impedance is the ratio of the open-circuit test stator voltage to the short-circuit test stator current. This ratio should be evaluated at a common value of field current such as I_f' shown in the plot above. Note that this value of field current is the value at which the OCC passes through the rated voltage of the synchronous machine.

The synchronous reactance will have a different value depending on whether or not the magnetic core is saturated. Note that the core is saturated on the OCC at the field current value of I_{f1}. If the magnetic core were unsaturated at this field current value, the OCC would continue along the linear portion of the curve which has been extended on the plot as the *air gap line* (AGL). The unsaturated value of the synchronous impedance is found according to

$$Z_{s,unsat} = \frac{V_1''}{I_1'} = \sqrt{R_a^2 + X_{s,unsat}^2}$$

such that the synchronous reactance is

$$X_{s,unsat} = \sqrt{\left(\frac{V_1''}{I_1'}\right)^2 - R_a^2}$$

If R_a is negligible, the unsaturated synchronous reactance is

$$X_{s,unsat} = \frac{V_1''}{I_1'}$$

Assuming the generator is connected to an infinite bus, the synchronous reactance at saturation is determined using the value of V_1 that occurs on the *modified air gap line* (MAGL). When the synchronous generator is connected to the infinite bus, its terminal voltage is raised to the rated value (where the core is saturated). After connection to the infinite bus, the terminal voltage of the generator will remain constant. If the field current is now changed, the generated voltage will change, not along the OCC curve, but along the modified air gap line. Thus, the synchronous impedance at saturation is given by

$$Z_{s,sat} = \frac{V_1'}{I_1'} = \frac{V_{1rated}}{I_1'} = \sqrt{R_a^2 + X_{s,sat}^2}$$

The saturated synchronous reactance is then

$$X_{s,sat} = \sqrt{\left(\frac{V_{1rated}}{I'_1}\right)^2 - R_a^2}$$

If R_a is negligible, the unsaturated synchronous reactance is

$$X_{s,sat} = \frac{V_{1rated}}{I'_1}$$

Example (Synchronous machine equivalent model)

The following data is obtained for a three-phase 10 MVA, 14 kV wye-connected synchronous machine (all voltages are line-to-line). The armature resistance is 0.07 Ω per phase.

I_f(A)	OCC (kV)	SCC (kV)	AGL (A)
100	9.0		
150	12.0		
200	14.0	490	18
250	15.3		
300	15.9		
350	16.4		

(a.) Find the unsaturated and saturated values of the synchronous reactance in Ω and pu.
(b.) Find the field current required if the synchronous generator is connected to an infinite bus and delivers rated MVA at 0.8 lagging power factor.
(c.) If the generator, operating as in part (b.), is disconnected from the infinite bus without changing the field current, find the terminal voltage.

The base quantities for pu calculations are:

$$S_{base} = 10^7 \text{ VA}$$
$$V_{base} = V_{1rated} = 14000/\sqrt{3} = 8083 \text{ V}$$
$$I_{base} = S_{base}/3V_{base} = 10^7 \text{ VA}/[3(8083)] \text{ V} = 412.4 \text{ A}$$
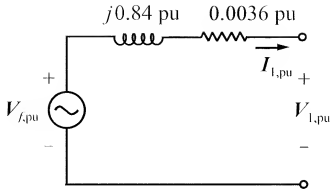$$Z_{base} = V_{base}/I_{base} = 8083/412.4 = 19.60 \text{ }\Omega$$

(a.)
$$V_1'' = \frac{18000}{\sqrt{3}} = 10392 \text{ V} \qquad I_1' = 490 \text{ A}$$

$$X_{s,unsat} = \sqrt{\left(\frac{V_1''}{I_1'}\right)^2 - R_a^2} = \sqrt{\left(\frac{10392}{490}\right)^2 - 0.07^2} = 21.2 \text{ }\Omega$$

$$X_{s,unsat,pu} = \frac{21.2}{19.6} = 1.08 \text{ pu}$$

$$V_1' = V_{1rated} = 8083 \text{ V} \qquad I_1' = 490 \text{ A}$$

$$X_{s,sat} = \sqrt{\left(\frac{V_1'}{I_1'}\right)^2 - R_a^2} = \sqrt{\left(\frac{8083}{490}\right)^2 - 0.07^2} = 16.5 \text{ }\Omega$$

$$X_{s,sat,pu} = \frac{16.5}{19.6} = 0.84 \text{ pu}$$

$$R_{a,pu} = \frac{0.07}{19.6} = 0.0036 \text{ pu}$$

(b.) Given that the machine is operating at rated load, the machine can be assumed to be operating in saturation. Thus, the equivalent circuit containing the saturated synchronous reactance is used.

$V_{1,\text{pu}} = 1 \angle 0^o$ pu

$PF = 0.8 \qquad \theta_v - \theta_i = \cos^{-1}(0.8) = 36.87^o$

$I_{1,\text{pu}} = 1 \angle -36.87^o$ pu

$V_{f,\text{pu}} = V_{1,\text{pu}} + I_{1,\text{pu}} Z_{s,\text{pu}}$

$\qquad = 1 \angle 0^o + (1 \angle -36.87^o)(0.84 + j0.0036)$

$\qquad = 1.649 \angle 23.97^o$ pu

$V_f = V_{base} \, V_{f,\text{pu}} = (14000 \text{ V})(1.649 \angle 23.97^o \text{ pu})$

$\qquad = 23.09 \angle 23.97^o$ kV

The corresponding field current is found from the MAGL (the MAGL is an open-circuit characteristic where $V_f = V_1$). The equation for the MAGL (slope = 14000V/200A = 70 V/A) is

$$V_1 = 70 I_f$$

such that the field current for $V_f = V_1 = 23.09$ kV is

$$I_f = \frac{V_1}{70} = \frac{23090}{70} = 329.9 \text{ A}$$

(c.) If the generator is disconnected from the infinite bus, then we jump from the MAGL to the OCC. For the same field current (I_f = 329.9 A), the corresponding terminal voltage is

$$V_1 = 16.25 \text{ kV}$$

## SYNCHRONOUS MACHINE POWER AND TORQUE

The complex power at the terminals of the synchronous machine can be determined using the equivalent circuit. For convenience, the machine terminals are used as the phase reference such that

$$V_1 = V_1 \angle 0^o \qquad V_f = V_f \angle \delta \qquad Z_s = Z_s \angle \theta_s$$

where δ is the phase angle of the generating voltage and θ_s is the phase angle of the synchronous impedance. The complex power at the terminals of the synchronous machine is

$$S = V_1 I_1^*$$

From the equivalent circuit, the current I_1 is
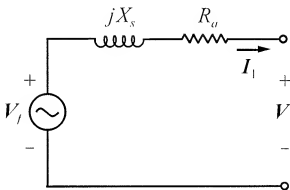
$$I_1 = \frac{V_f - V_1}{Z_s} = \frac{V_f}{Z_s} \angle (\delta - \theta_s) - \frac{V_1}{Z_s} \angle (-\theta_s)$$

The conjugate of I_1 is

$$I_1^* = \frac{V_f}{Z_s} \angle (\theta_s - \delta) - \frac{V_1}{Z_s} \angle \theta_s$$

The resulting per phase complex power is

$$\boldsymbol{S} = V_1 I_1^* = \frac{V_1 V_f}{Z_s} \angle (\theta_s - \delta) - \frac{V_1^2}{Z_s} \angle \theta_s$$

The real power and reactive power are

$$P = \frac{V_1 V_f}{Z_s} \cos(\theta_s - \delta) - \frac{V_1^2}{Z_s} \cos \theta_s$$

$$Q = \frac{V_1 V_f}{Z_s} \sin(\theta_s - \delta) - \frac{V_1^2}{Z_s} \sin \theta_s$$

If the effective armature resistance is neglected ($R_a = 0$), the magnitude of the synchronous impedance becomes the magnitude of the synchronous reactance ($Z_s = X_s$) with $\theta_s = 90°$ and the per-phase expressions for P and Q reduce to

$$P = \frac{V_1 V_f}{X_s} \sin \delta$$

$$Q = \frac{V_1 V_f}{X_s} \cos \delta - \frac{V_1^2}{X_s}$$

For a three-phase synchronous machine, we have

$$P_{3\phi} = \frac{3 V_1 V_f}{X_s} \sin \delta = P_{max} \sin \delta$$

$$Q_{3\phi} = P_{max} \cos \delta - \frac{3 V_1^2}{X_s}$$

where

$$P_{max} = \frac{3 V_1 V_f}{X_s}$$

The stator losses have been neglected by assuming $R_a = 0$, so that the real power at the synchronous machine terminals is equal to the air gap power which is equal to the developed torque times the angular velocity of the machine.

$$P_{3\phi} = T\omega_s$$

$$T = \frac{P_{3\phi}}{\omega_s} = \frac{3 V_1 V_f}{\omega_s X_s} \sin \delta = \frac{P_{max}}{\omega_s} \sin \delta = T_{max} \sin \delta$$

where

$$T_{max} = \frac{3 V_1 V_f}{\omega_s X_s}$$

Note that the power and the torque vary as the sin of the angle δ which is known as the *power angle* or *torque angle*. The synchronous machine will stay at synchronous speed if it is loaded gradually up to the limit of P_{max} for a generator or T_{max} for a motor. But the machine loses synchronism if the power angle goes greater than 90°. The value of maximum torque T_{max} is known at the *pull-out torque*. Note that the value of the pull-out torque can be increased by increasing the value of V_f. Thus, a synchronous motor that tends to lose synchronism due to excessive torque can be brought back into synchronism by increasing the field current. A synchronous generator may lose synchronism because the prime mover tends to rotate the machine at speeds above the synchronous speed. The synchronous generator can be brought back into synchronism by increasing the field current, which increases the counter-torque, and slows the machine down to synchronous speed.

Example (Synchronous generator / complex power)

A three-phase 5kVA, 208 V, four-pole, 60 Hz wye-connected synchronous machine has negligible stator winding resistance and a synchronous reactance of 8 Ω per phase at rated voltage. The machine is operated as a generator in parallel with a three-phase 208V, 60 Hz power supply.

(a.) Determine the generator voltage and the power angle when the machine is delivering rated kVA at 0.8 PF lagging. Draw the phasor diagram.

(b.) With the same field current as in part (a.), the power of the prime mover is slowly increased. Determine the values of the stator current, power factor, real power and reactive power at the maximum power transfer condition.

$$V_{1rated} = \frac{V_{LL}}{\sqrt{3}} = \frac{208}{\sqrt{3}} = 120 \text{ V}$$

$$I_{1rated} = \frac{S}{\sqrt{3} \, V_{LL}} = \frac{5000}{\sqrt{3}\,(208)} = 13.88 \text{ A}$$

$V_1 = 120 \angle 0^o$ V

$PF = 0.8$ lagging

$\theta_v - \theta_i = \cos^{-1}(0.8) = 36.87^o$
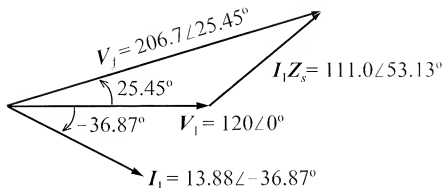
$I_1 = 13.88 \angle -36.87^o$ A

$V_f = V_1 + I_1 Z_s$

$\quad = 120 \angle 0^o + (13.88 \angle -36.87^o)(8 \angle 90^o)$

$\quad = 120 \angle 0^o + 111.0 \angle 53.13^o$

$\quad = 206.7 \angle 25.45^o$ V $= V_f \angle \delta$

$V_f = 206.7$ V $\qquad \delta = 25.45^o$

$V_1 = 206.7 \angle 25.45°$

$25.45°$

$I_1 Z_s = 111.0 \angle 53.13°$

$-36.87°$ $V_1 = 120 \angle 0°$

$I_1 = 13.88 \angle -36.87°$
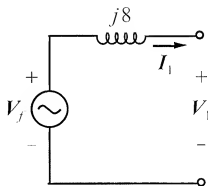
(b.) V_1, V_f stay constant, δ changes,
Maximum power condition $\Rightarrow$ $\delta = 90°$
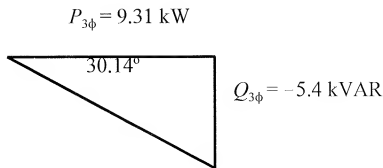
$V_f = 206.7 \angle 90°$

$$P_{3\phi} = P_{max} \sin\delta = P_{max} = \frac{3 V_1 V_f}{X_s} = \frac{3(120)(206.7)}{8} = 9.31 \ \text{kW}$$

$$Q_{3\phi} = P_{max} \cos\delta - \frac{3 V_1^2}{X_s} = -\frac{3 V_1^2}{X_s} = -\frac{3(120)^2}{8} = -5.4 \ \text{kVAR}$$

$$I_1 = \frac{V_f - V_1}{jX_s} = \frac{206.7 \angle 90° - 120 \angle 0°}{8 \angle 90°} = 29.88 \angle 30.14° \ \text{A}$$

$PF = \cos(30.14°) = 0.865 \ \text{leading}$

$P_{3\phi} = 9.31 \ \text{kW}$

$30.14°$

$Q_{3\phi} = -5.4 \ \text{kVAR}$

Example (Synchronous motor)

The synchronous machine defined in the previous example is operated as a synchronous motor when fed from a three-phase 208 V, 60 Hz supply. The field excitation is adjusted so that power factor is unity when the machine draws 3 kW from the supply.
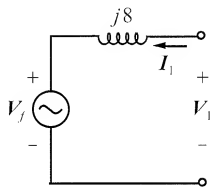- (a.) Determine the excitation voltage and the power angle. Draw the phasor diagram.
- (b.) If the field excitation is held constant and the shaft load is slowly increased, determine the maximum torque (*pull-out torque*) that the motor can deliver.

(a.) $V_1 = 120 \angle 0^o$ V

$PF = 1.0 \qquad \theta_v - \theta_i = 0^o$

$P = 3 V_1 I_1 = 3(120) I_1 = 3$ kW
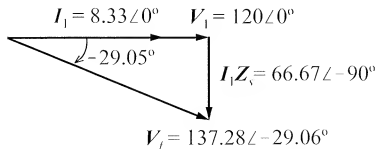
$I_1 = \dfrac{3000}{3(120)} = 8.33$ A

$V_f = V_1 - I_1 Z_s = 120 \angle 0^o - (8.33 \angle 0^o)(8 \angle 90^o)$

$\qquad = 120 \angle 0^o - 66.67 \angle 90^o$

$\qquad = 137.28 \angle -29.06^o$ V $= V_f \angle \delta$

$V_f = 137.28$ V $\qquad \delta = -29.06^o$

Phasor diagram:
$I_1 = 8.33 \angle 0^o$ $V_1 = 120 \angle 0^o$
$\angle -29.05^o$
$I_1 Z_s = 66.67 \angle -90^o$
$V_f = 137.28 \angle -29.06^o$

(b.) V_1, V_f stay constant, δ changes,
Maximum power condition $\Rightarrow \delta = 90^\circ$

$$V_f = 137.28 \angle 90^o$$

$$P_{max} = \frac{3\,V_1 V_f}{X_s} = \frac{3(120)(137.28)}{8} = 6.18\,\text{kW}$$

$$T_{max} = \frac{P_{max}}{\omega_s} \qquad \omega_s = \frac{n_s}{60}\,2\pi \qquad n_s = 120\frac{f}{p}$$

$$\omega_s = 4\pi\frac{f}{p} = 4\pi\frac{60}{4} = 188.5\,\text{rad/s}$$

$$T_{max} = \frac{6180}{188.5} = 32.8\,\text{N-m}$$

STARTING SYNCHRONOUS MOTORS

Unlike the induction motor, the synchronous motor is not self-starting (it cannot simply be connected to the AC supply to start). If a synchronous motor is connected directly to the AC supply, it will simply vibrate. The inertia of the rotor prevents it from locking onto the rotating stator field. Two techniques are commonly used to start an synchronous motor.

Variable-Frequency Supply - The synchronous motor can be started with a frequency converter (variable frequency output) by slowly increasing the frequency of the stator field upon startup. This allows the rotor time to overcome the inertia required for it to follow the stator field as it increases in speed. The primary drawback to this technique is the cost of the frequency converter.

Starting the Synchronous Motor as an Induction Motor - Additional windings known as *damper* windings can be added to the synchronous motor to allow it to start as an induction motor. The damper windings closely resemble the cage of an induction motor. To start the induction motor, no DC current is passed through the field winding initially. When the motor is connected to the supply, the synchronous motor will start like an induction motor as currents are induced in the damper windings. The motor will increase speed until it reaches a speed slightly less than synchronous speed. At that time, the DC field current is applied to the rotor. Since the rotor is closely following the stator field, it quickly increases speed to the synchronous speed and locks onto the rotating stator field. Note that the damper windings have no induced currents as the synchronous motor rotates at the synchronous speed. The damper windings have another function as they help keep the synchronous motor in synchronism. If the synchronous motor speed increases or decreases away from the synchronous speed, currents are induced in the damper windings that tend to oppose the change in speed.

[54] ELECTRICAL GENERATOR HAVING NON-SALIENT POLES FOR METERING SHAFT ROTATION OF A TURBINE ASSEMBLY

[75] Inventor: Paul W. Geery, Houston, Tex.

[73] Assignee: Dresser Industries, Inc., Dallas, Tex.

[22] Filed: Oct. 20, 1971

[21] Appl. No.: 191,126

Related U.S. Application Data

[62] Division of Ser. No. 866,850, Oct. 16, 1969, Pat. No. 3,636,392.

[52] U.S. Cl. ....73/231 R
[51] Int. Cl. G01f 1/06
[58] Field of Search 73/229–231;
310/156; 324/174

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Primary Examiner—Herbert Goldstein
Attorney—Robert W. Mayer et al.

[57] ABSTRACT

A cup-shaped member is attached to a rotating shaft as might be associated with a turbine meter for measuring fluid flow or volume. A permanent magnet ring is mounted internal to the cup member, the ring having a plurality of equispaced alternating north and south poles. A second cup-shaped member is mounted within the permanent magnet ring having a plurality of coils mounted on an iron core therein having non-salient poles, whereby uniform reluctance in the magnetic circuit is maintained regardless of the angular position of the shaft.

In an alternative embodiment, the ring is iron, having the coils mounted thereon, and the permanent magnet is made to rotate in the center portion of the ring.

Circuitry is also described to convert the voltage output from the generator into fluid volume indications as dictated by the rotation of the shaft, such circuitry including a first rectifier connected to an alternating voltage, a rechargeable battery connected to the output of the first rectifier, a second rectifier connected to the alternating voltage and a trigger flip-flop circuit powered by the rechargeable battery and connected to the output of the second rectifier whereby a series of sharply squared output pulses are produced at the output of the trigger circuit in response to the rotation of the shaft. In addition, circuitry is provided for scaling down the number of sharply squared output pulses by a predetermined number whereby the output of the scaling circuit provides a predetermined number of output pulses according to the conventional units of flow as determined by the rotation of the shaft.
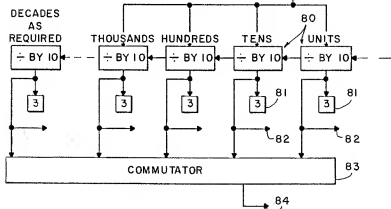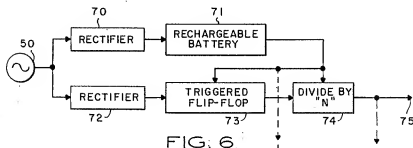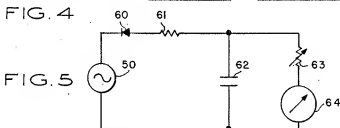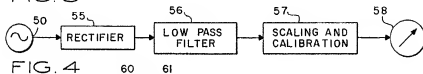
2 Claims, 15 Drawing Figures
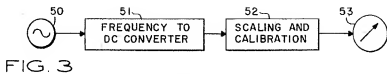
FIG. 1

FIG. 2

FIG. 12

FIG. 13

FIG. 14

FIG. 3

FIG. 4

FIG. 5

FIG. 6
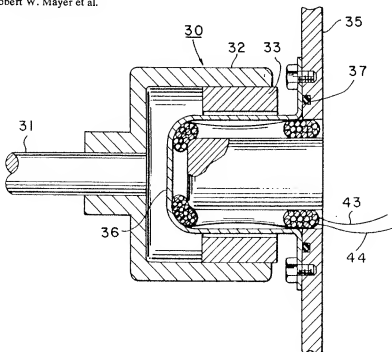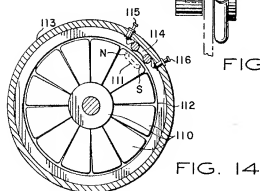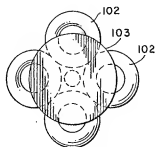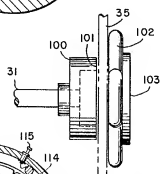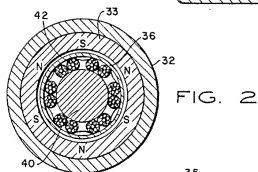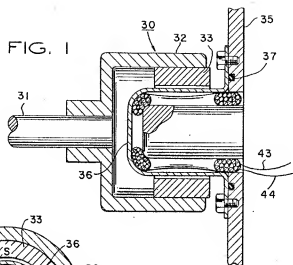
FIG. 7
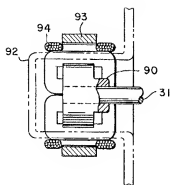
FIG. 8

FIG. 9

FIG. 10

FIG. 11

PRIOR ART

FIG. 15

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ELECTRICAL GENERATOR HAVING NON-SALIENT POLES FOR METERING SHAFT ROTATION OF A TURBINE ASSEMBLY

This is a division of application Ser. No. 866,850, filed Oct. 16, 1969, Now U.S. Pat. No. 3,636,392.

BACKGROUND OF THE INVENTION

This invention relates generally to fluid flow meters, and in particular to those meters wherein shaft rotation is related to the volume of fluid. Even more particularly, the invention relates to apparatus and electrical circuitry for metering such shaft rotation.
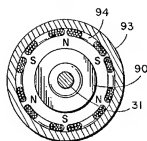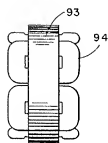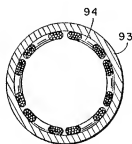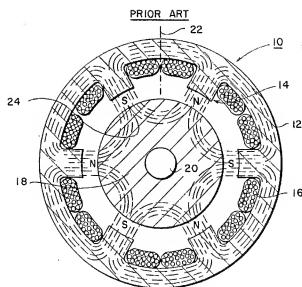
Meters used for the measurement of fluid flow, especially of the turbine and positive displacement rotor types, have a fixed relation of volume flow to rotor shaft revolution. The art has attempted to monitor the shaft rotation by various means, one of which employs a speed reducing gear train coupled to the rotor shaft which drives a mechanical totalizing counter/register to indicate total cumulative volume units in visible decade digits. Such a system, while being mechanically simple, is impractical for providing either an instantaneous rate of flow or a remote readout.

Still another conventional approach employs a switch having one or more contacts which close in response to the rotation of the meter shaft. This could, for example, be a reed relay which is responsive to a magnet mounted on the rotating shaft. The switch contacts for such a device are normally connected to electrical circuitry to either directly advance an electrically pulsed mechanical counter/register, or the switch closures are electrically counted down by a predetermined ratio to drive the pulsed counter register in the proper units. However, for high rotor shaft speeds, switch closure speed may restrict usefulness. Likewise, the lifetime of the switch contacts often limits practical applications.

Another problem relating to monitoring the shaft rotation resides in the very limited amount of torque output available from the rotor shaft, whether it be an impellor, turbine or rotary positive displacement meter for fluids.

It is therefore the primary object of this invention to provide a new and improved apparatus for metering the rotation of a rotating shaft;

It is another object of the invention to provide apparatus for metering rotation of a rotating mechanism; and

It is still another object of the invention to provide apparatus and related electrical circuitry for producing various electrical indications of rotational activities having a limited amount of torque.

The objects of the invention are accomplished, briefly, by a new and improved electrical generator apparatus associated with the shaft rotation wherein the reluctance of the air gap in the magnetic circuit is constant for all angular positions of a rotating magnet attached or connected to the shaft, thus enabling the device to utilize the very low torque output available. The uniform reluctance eliminates magnetic detenting or "toothing" as it is known in the art.

These and other objects, features, and advantages of the invention will become apparent to those skilled in the art from a reading of the following detailed description and drawing, in which:

FIG. 1 illustrates in cross section an electrical generator according to the present invention;

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FIG. 2 illustrates in another cross section the generator according to FIG. 1;

FIG. 3 illustrates in block diagram circuitry for converting an alternating voltage to a rate of fluid flow;

FIG. 4 illustrates in block diagram alternative circuitry for converting an alternating voltage to a rate of fluid flow;

FIG. 5 illustrates in block diagram circuitry for using the meter rotor speed versus voltage amplitude relationship for indicating rate of flow;

FIGS. 6 and 7 illustrate in block diagram the preferred embodiment of the invention for converting the alternating voltage to a fluid volume rate, as well as circuitry for cumulative storage of total fluid volume flow.

FIG. 8 illustrates in cross section the finished generator according to FIG. 11;

FIG. 9 illustrates in another cross section the generator according to FIG. 8;

FIG. 10 illustrates a top plan view of the coil assembly on the generator according to FIG. 11;

FIG. 11 illustrates in cross section the preliminary construction stage of an alternative embodiment of an electrical generator according to the present invention;

FIG. 12 illustrates in cross section an alternative embodiment of the generator according to the invention;

FIG. 13 illustrates schematically the coil arrangement for the generator according to FIG. 12;

FIG. 14 illustrates an alternative means for metering the rotation of a turbine blade; and

FIG. 15 illustrates in cross section an electrical generator according to the prior art.

Referring now to the drawing in more detail, especially to FIG. 15, there is illustrated an electrical generator 10 embodying principles of the prior art. A soft iron ring 12 having a plurality of islands 14 constitutes the armature of the generator. A plurality of coils 16 are mounted, respectively, between the islands 14, one coil being provided for each island such that each coil actually surrounds an island. Such islands are referred to by those in the art as "salient poles," the purpose for which will be explained hereinafter.

Centered within the ring 12 is a rotating permanent magnet 18 having a plurality of alternating magnetic north and south poles, identified in the drawing by the letters N and S. A shaft 20 in the center of the magnet 18 enables the magnet 18 to rotate.

In the design of such prior art generators, the salient poles cause the magnetic reluctance of the flux path to alternately increase and decrease as the magnet 18 rotates. Thus as the S pole 24 rotates clockwise approximately 30° to the position indicated by the dotted line 22, the air gap is seen to increase between the pole and the ring 12.

Magnetic flux always seeks the lowest reluctance path and the alignment with the lowest reluctance flux paths supports the highest flux density. The permanent magnet rotor 18 always tends to be drawn into the low reluctance alignment and resists displacement from that position. When forcibly rotated by external shaft drive, the rotor 18 presents successively:

A high positive torque load to start from the aligned position (as illustrated in FIG. 15);

A decreasing torque load at 15°;

Near zero torque load at 30°;

An increasing negative torque load at 45° as it is attracted toward the next alignment position; and

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Finally a high positive torque load as it passes beyond the 60° position (the next island) to repeat the sequence.

The cyclicly varying torque load pattern gives rise to the descriptive term "cogging" or "magnetic detenting." When the external driving force is reduced to a low value or removed, the rotor 18 seeks to align its pole faces with the nearest island 14 (armature pole face), whether it be required to move forward or backward, and will rotate to the aligned position as though a detent device were dictating a preferred rest position.

Thus it should be appreciated that such prior art devices while providing increased voltage and current capabilities, cannot be used for applications where only a low amount of torque is available.

FIGS. 1 and 2 illustrate a generator 30 built in accordance with the present invention. A rotatable shaft 31, for example, as might be caused to rotate as in the U. S. Pat. No. 3,429,182 issued to Wemyss, has attached thereto a cup-shaped member 32, preferably non-magnetic, having a permanent magnet ring 33 affixed to the internal surface of the member 32. It should be appreciated, however, that the type of mechanism causing the shaft 31 to rotate forms no part of this invention and is therefore not to be considered a limiting factor. The magnet ring 33 has magnetized into its inner surface a plurality of equispaced magnetic pole faces.

Attached to the meter body cavity wall 35 is a second cup-shaped member 36 constructed, for example, of stainless steel. The O-ring 37 provides a seal between the cup 36 and the wall 35.

Located within the cup 36 is a magnetically permeable non-salient cylindrical core 40 constructed, for example, of iron. Equispaced around the outer periphery of the core 40 is a plurality of coil windings 42, one coil for each of the pole faces on the ring 33. Thus, for six pole faces (three North, three South), there should preferably be six coils 42. For convenience of construction, the induction coils can be cemented onto the core if desired. As shown in FIG. 1, the conductors 43 and 44 from the coil windings 42 are used for the voltage output from the coils which are preferably connected series-aiding in a manner well-known in the art. However, where low voltages are acceptable, and more current capability is desired, the coils could be connected in parallel. The coil connections could be modified to the extent that they are brought out separately.

It should be appreciated that the distance between the core 40 and the ring 33 is constant, regardless of the angular position of the rotating shaft; hence, the reluctance of the magnetic circuit remains constant, with no "detenting" or "cogging."

In the operation of the generator of FIGS. 1 and 2, the flux external to the magnetic ring 33 penetrates the wall of the cup 36, the annular coil space, traverses a portion of the core 40, returns through the coil space and the wall of the cup 36 to re-enter the magnet at an opposing pole face. When the shaft 31 causes the magnetic ring 33 to rotate, a sinusoidal alternating voltage is generated in the coils 42 and appears on the conductors 43 and 44. Although other combinations of pole faces and coils can be used, six coils and six pole faces generates three cycles of alternating voltage per revolution of the shaft 31. Since all of the moving parts are

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located within the meter body cavity, there is an additional advantage in having no need to provide a fluid-tight seal between moving parts. Thus, it should be appreciated that, by having the shaft 31 rotation be of the type proportional to volume flow, there will appear at the conductors 43 and 44 an alternating voltage proportional to volume flow.

FIG. 3 illustrates in a simplified block diagram circuitry for indicating volume flow. The generated voltage 50 (from conductors 43 and 44) is coupled into a conventional FREQUENCY TO DC CONVERTER 51, from which the resulting DC signal is coupled through conventional scaling and calibration circuitry 52 to a DC meter 53. Thus, by well-known methods and means, the meter 53 is calibrated to read rate of flow in appropriate units of volume and time.

FIG. 4 illustrates alternative circuitry in block diagram. Instead of using the frequency of the voltage output as in FIG. 3, the amplitude of the voltage is used to provide an indication of volume flow. The generated voltage is coupled through a rectifier circuit 55, a low pass filter 56 and the scaling and calibration circuitry 57 into a DC meter 58. Thus, the meter 58 is calibrated to indicate rate of flow in appropriate units of volume and time.

FIG. 5 illustrates in block diagram circuitry utilizing the rotor shaft 31 speed versus voltage amplitude relationship for indicating the rate of flow. The negative portion of the generated voltage is coupled into a high impedance RC low pass filter through the rectifier 60, the resistor 61 and capacitor 62 forming the low pass filter. The negative going voltage peaks are loaded by the calibrating (scaling) and ambient temperature compensating network 63, and the DC microammeter 64. This particular arrangement is totally powered by the generated voltage 50. By prohibiting other load connections to the negative half cycles of the generated voltage 50, the accuracy of the rate of flow is maintained. The positive going half cycles are used for other instrumentation circuit loads as desired (not shown). It should be appreciated, however, that the rate of flow could be obtained from the positive cycles and the negative half cycles could then be used for the additional instrumentation.

FIGS. 6 and 7 illustrate in block diagram a more detailed description of circuitry for converting the generated voltage 50 into an indication of volumetric rate of flow according to the preferred embodiment of the invention. The positive half cycles of voltage 50 are coupled through the half-wave rectifier and current-limiting diode combination 70 into a rechargeable battery 71, for example, a nickel-cadmium battery, which is used to supply the small amount of power needed for the various trigger and counter circuits. The positive half cycles of voltage 50 are also coupled through a second half-wave rectifier current-limiting diode combination 72 into a triggered flip-flop circuit 73, for example, a Schmitt trigger. The sharply squared output pulses from the trigger circuit 73 are counted down by the N-Divider circuit 74 by the required scaling factor to produce one output pulse for each unit of volume flow through the meter (not shown). The pulse output appearing at terminal 75 may be remotely accumulated (not illustrated) to register total flow volume through the meter. It should be appreciated that the time rate of

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pulse will also provide rate of flow. For example, the pulse output may be sensed by recognizing logic level voltage changes at the counter output, the logic levels can actuate a solid state switch which may be monitored, or a relay contact closure can be actuated and the contact status may be recognized remotely.

Meters used for monitoring volumetric rate of flow are normally designed such that many rotor revolutions are required to pass a basic unit of volume; hence, the generator device (as in FIG. 1) should preferably be of multiple pole design. In practical designs, the generator and related circuitry produces several thousand pulses from the trigger circuit 73 to be exactly equal to a volume unit of flow through the meter (not shown). It has been discovered that it is possible to arrange the scaling counter/divider circuitry in such a way that meter calibration can be achieved to great accuracy by adjusting the counter/divider ratio in predetermined exact small increments of volume flow units, for example, one tenth of one percent steps.

A typical model of meter now commercially available is designed such that 90 rotor shaft revolutions should pass exactly 1 cubic foot of gas. Fitting such a meter (not shown) with a six pole electric generator according to the invention produces three cycles of alternating voltage per shaft revolution, or 270 pulses of voltage at the output of the trigger circuit 73 for one cubic foot of gas passing through the meter. A conventional unit of flow to be totaled is 100 cubic feet, so that the trigger pulses should be divided by 27,000 to yield one output pulse for each 100 cubic feet of gas to be metered. With an electronic counter, it is convenient to divide by 27 in a first counter and by 1,000 in a following counter. Appropriate wiring connections of the counter circuitry can be chosen to adjust the counter by steps of one count. This change of the counter division ratio by 1 part in 1000 provides an available meter calibration step of one tenth of one percent. Should the meter be not absolutely perfectly dimensioned and prove to be in error by plus or minus a known percentage, the "Divide by 1,000" counter can be adjusted correspondingly to a higher or lower count ratio than 1,000. For example, it can be made 1,001 or 999 for a 0.1 percent calibration correction. Calibration can then be made to within plus or minus 0.05 percent true.

This particular counter system is readily adaptable to a variety of meter sizes and types by adjusting the first counter divider to correspond with the shaft revolution/volume ratio of the given meter design, and preserving a sufficiently large countdown division in the second counter to keep the incremental calibration steps acceptably small.

FIG. 7 illustrates in block diagram additional count storage functions with local and/or remote visual or electronic readout of totalized meter volume flow as dictated by the output pulses from the "Divide By N" circuitry 74. The pulses from circuit 74 are coupled into a digital counter series 80 to continuously accumulate and store the total volume flow. Visual readout indicators 81 can be electrically driven either locally or remotely to display the contents of the totalizer counter in decade digit form. In FIG. 7, the digital counters 81 are illustrated as reading "33333." The contents of the totalizer storage counter may also be

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read out remotely, as from the output terminals 82, electrically in parallel bit form, or commutated by the commutator 83 and read out in serial bit form from the output terminal 84.

If desired, the totalizer storage counter could be a straight binary counter and the digital electronic readout would be in parallel bit binary form, or, if commutated, in binary form serial by bit. In such an embodiment, the visual readout indicators to display decade digit form would require a binary to decimal interfacing converter.

FIGS. 8, 9, 10 and 11 illustrate various views of an alternative embodiment of the electrical generator according to the invention. Attached to the rotatable shaft 31 is a permanent magnet 90 having a plurality, for example six, equispaced pole faces around its periphery, alternately marked as N, S and N, etc. A stationary, non-magnetic cup member 92, which could be sealably attached to the meter body wall (not shown) as in FIG. 1, encloses the permanent magnet 90. A non-salient ring 93 of a magnetically permeable material, for example iron, is fabricated around the external surface of the cup 92, with a plurality of magnetic coils 94, for example six, located between the magnet 90 and the ring 93, as is best illustrated in FIG. 9. Thus it should be appreciated that the generator of FIGS. 8 and 9, as is the case for the generator of FIG. 1, has a constant reluctance in the magnetic circuits associated with its coils, magnet pole faces and magnetic permeable ring, and that it likewise does not exhibit "detenting" or "cogging" as is characteristic of prior art generators.

FIG. 10 illustrates a top plan view of the coils 94 shown in cross section in FIGS. 8 and 9 in relation to the ring 93.

FIG. 11 illustrates on cross section the ring 93 and coil assembly 94 prior to insertion of the rotating magnet 90 on the rotatable shaft 31.

FIG. 12 illustrates an alternative embodiment of a generator having a constant reluctance in its associated magnetic circuits. The cup 100 has a plurality of magnetic pole faces 101 on its surface nearest the wall 35. There could be, for example, four faces, two north and south. On the other side of the non-magnetic cavity 45 wall 35 is mounted a plurality of round bobbin or pie-shaped coils 102, for example, four, best illustrated in FIG. 13. Mounted external to the coils is a magnetically permeable plate member 103 constructed, for example, of iron. As with the other embodiments illustrated and described herein, the path between the magnetic pole faces and the magnetically permeable member remains constant for all positions of the shaft 31.

FIG. 14 illustrates still another embodiment of an electrical generator having a constant reluctance in its magnetic circuits. A vaned turbine wheel rotor 110 has a permanent magnet 111, having north and south pole faces embedded or otherwise attached to one or more of its rotor blades. A non-magnetic internal fixed fairing sleeve 112 envelopes the rotor blades. External to the sleeve 112 is a casing 113 of magnetically permeable material, for example, of iron. Mounted on the internal surface of the casing 113 is one or more coils 114 having electrical output connections 115 and 116. Due to the constant distance between the magnet 111 and the casing 113 the generator of FIG. 14 is seen to have a constant reluctance for all positions of the turbine blades.

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Thus there has been described and illustrated herein various embodiments of generators having constant reluctance and which fail to exhibit the detenting and cogging characteristic which have heretofore kept electrical generators from being used in low torque applications. There has also been described new and useful circuitry for using such generators. Obvious modifications of the embodiments described herein will occur to those skilled in the art. For example, the generator according to the invention would perform exactly as described if the permanent magnet were relieved or notched between adjacent north and south poles, leaving it star-shaped, or, it could be actually a bar magnet, or the U shaped magnet in the rotor blade tip. In these cases the permanent magnet poles would now be visually prominent and conspicuous in form and therefore salient, even though the reluctance paths would still have no salient (prominent and conspicuous) variations with shaft position. It is important only that there be no salient poles on the armature assembly to cause changes in the reluctance of the magnetic flux path as the permanent magnet is rotated. The magnetic poles exist as finite areas on the permanent magnet surface and on a cylindrical or ring-shaped magnet are not visible or conspicuous (non-salient). If the magnet is bar-shaped, U-shaped or star-shaped, the pole faces are then conspicuous and the magnet form is then described as salient. However, this would not affect the non-salient armature form disclosed here to achieve the performance described. Furthermore, although the preferred embodiment contemplates an iron core, the assemblies described herein are also operative if the magnetically permeable member were absent, as with air, or were made of some non-conductive material having a magnetic permeability of one. However, these embodiments have been presented as being illustrative only of the invention and should not be construed in a limiting sense.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

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1. An apparatus for metering the rotational activity of a turbine assembly, comprising:

a rotatable turbine assembly having a vaned turbine wheel rotor, said turbine wheel rotor having at least one rotor blade;

a permanent magnet embedded in the tip of said at least one blade;

a ring-shaped non-salient member of magnetically permeable material enclosing said turbine wheel rotor;

at least one induction coil mounted on the internal surface of said ring;

conductor means connected to said at least one coil for monitoring the alternating voltage induced in said at least one coil relating to the rotation of said rotor; and

means for converting the frequency of said alternating voltage into an indication of the rate of rotation of said shaft, said means for converting the frequency comprising:

a first rectifier connected to said alternating voltage;

a rechargeable battery connected to the output of said first rectifier;

a second rectifier connected to said alternating voltage; and

a trigger flip-flop circuit powered by said rechargeable battery and connected to the output of said second rectifier, whereby a series of sharply squared output pulses are produced at the output of said trigger circuit responsive to the rotation of said shaft.

2. The apparatus according to claim 1, including in addition thereto circuit means for scaling down the number of sharply-squared output pulses by a predetermined number whereby the output of said scaling circuit provides a predetermined number of output pulses according to conventional units of flow as determined by the rotation of said shaft.

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